

Impacts of Soil and Pipe Thermal Conductivity on Performance of Horizontal Pipe in a Ground-source Heat Pump

Yan Song

Doctoral Candidate

Yang Yao

Professor

Wei Na

Doctoral Candidate

Department of Building Thermal Engineering, Harbin Institute of Technology
Harbin P. R. China, 150090
hitsy@126.com

Abstract: In this paper the composition and thermal property of soil are discussed. The main factors that impact the soil thermal conductivity and several commonly-used pipe materials are studied. A model of heat exchanger with horizontal pipes of ground-source heat pump is developed. The impact of soil thermal conductivity and pipe thermal conductivity on the soil temperature field around the buried pipe, and the thermal performance of the heat exchanger are simulated. The simulation results show that with the increase of soil thermal conductivity, heat transfer quantity obviously increases, and the temperature of soil around pipe decrease under winter conditions. The temperature field varies relatively faster with thermal conductivity in the site nearer to the buried pipe. With the increase of pipe thermal conductivity, heat transfer quantity and the mean temperature of the buried pipe's outside surface all increase.

Key words: ground-source heat pump (GSHP); horizontal pipe; soil thermal conductivity; pipe thermal conductivity; soil temperature field

1. INTRODUCTION

As an energy-saving and environment friendly air conditioning technology, ground-source heat pump has been utilized wildly for some years. It is necessary to study in detail soil property and pipe material for utilizing GSGP successfully.

2. COMPOSITION AND THERMAL PROPERTY OF SOIL

Soil is a kind of complicated substance with its

unhomogeneity and multiphase. In order to be understand easily, it is used to be divided into mineral substance (solid state), organic matter (solid state), water (liquid state) and air (gas state), seen from Table 1. It is necessary and important to study soil property for utilizing GSGP successfully. And thermal property of soil includes: soil heat conduction coefficient (thermal conductivity), density, specific heat, temperature, thermal resistance and thermal diffusion degree, etc..

Soil thermal conductivity is the most important property parameters, and a lot of complicated problem involved in heat transfer between buried pipe and soil in GSHP, such as freezing and thaw of soil, flow of groundwater, simultaneous conduction of heat and wet etc., can be simplified by using an equivalent thermal conductivity of soil, which can be obtained by measuring and analyzing through experiment.

Comprehensive research shows that Soil thermal conductivity is related greatly to the moisture, density and temperature of soil, in addition the size, distribution and space rate of particles in soil^[1].

(1) Moisture. Determined by the experiment, the thermal conductivity of ordinary soil with its temperature $10 \sim 40^{\circ}\text{C}$, is $2.3\text{W}/(\text{m}\cdot\text{K})$ under the condition of ordinary moisture, $0.55\sim 0.6\text{W}/(\text{m}\cdot\text{K})$ under the desiccation state, and $2.7\text{W}/(\text{m}\cdot\text{K})$ under the waterlogged condition^[2]. With the increase of the moisture, soil thermal conductivity increases, but this trend of increasing is diminished gradually. And when moisture increases to a certain specific value, the thermal conductivity is relatively invariable.

(2) Density. The bigger soil density is, the greater

* Corresponding author. Tel.: +86 451 82339810;
Fax.: +86 451 86282123; E-mail address: hitsy@126.com

Tab. 1 Main parameters of composition in soil (standard atmosphere, 20°C)

Composition	Density kg/m ³	Specific heat of quality kJ/(kg·°C)	Specific heat of volume kJ/(m ³ ·°C)	Thermal conductivity W/(m·°C)
Mineral substance (similar to the average)	2650	0.733	1942	2.93~8.37
Organic matter (similar to the average)	1300	1.926	2504	0.251
Water	1000	4.186	4187	0.595
Air	1.2	1.005	1.2	0.026

through the experiment to calculate soil thermal conductivity under different moisture and different density.

$$\lambda_s = 0.144166 \times [0.9 \times \log(n \times 100) - 0.2] \times 10^{0.000024 \rho_s}$$

Where n denotes soil moisture (kg/kg) and ρ_s is density of soil, kg/m³.

(3) Temperature. In ordinary condition, the increase of temperature results in a increase of soil thermal conductivity, and when temperature increases within the range of 20°C, soil thermal conductivity increases about 0.1~0.2 W/(m·K). But once soil is frozen, the property and performance of melt soil and frozen soil is absolutely different. Measured with experiments, the thermal conductivity of inferior clay is 1.616 W/(m·K) under its melt state and 2.454 W/(m·K) under its frozen state. So generally speaking, soil thermal conductivity of frozen state should be greater compared with that of melting. This is mainly because the heat conduction coefficient of the liquid water is 0.58W/(m·K), while that of ice (0°C) is 2.25 W/(m·K).

3. MATERIAL AND THERMAL PROPERTY OF BURIED PIPE

It is important to select suitable material for buried pipe. In the fifties of the 20th century, the metal pipes are generally adopted, such as the zinc-plated steel and the copper pipes. Until later stage of the seventies, they are replaced by the silent stock pipes. Though the heat conduction performance of the silent stock pipe is worse than that of the metal, its thermal resistance is matched with that of soil well, and the anticorrosive performance is good, silent stock pipes

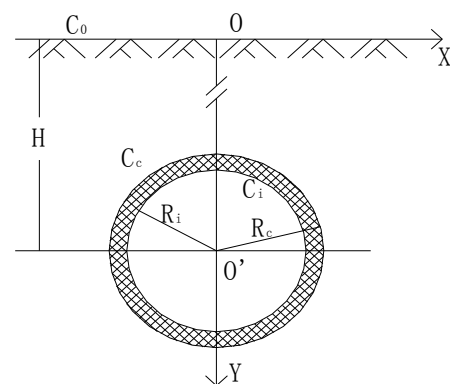
are applied extensively. Table 2 gives several commonly used pipes and their thermal conductivity

Tab. 2 The types of the buried pipe and their thermal conductivities

Type of pipe	Symbol	Thermal conductivity W/(m·°C)
Polyvinyl chloride pipe	PVC	0.14~0.19
polyethylene pipe with little density	PE	0.35
polyethylene pipe with high density	PE	0.43~0.52
Polypropylene pipe	PP-R	0.24
Polybutylenes pipe	PB	0.23
Aluminum-plastic pipe	PAP	0.45

4. MODEL AND ITS SOLVING

The horizontal pipe of the heat exchanger in GSHP is considered as research object, as shown in Fig. 1. And its two-dimension mathematics model is developed, which is one of cylinder theory models.

**Fig. 1 Cutaway view of physical model of horizontal buried pipe**

The model is solved by using the conformal mapping, separating the variable, and boundary

discretization methods^[4,5]. The series solutions for the temperature field around the pipe and in the ground were obtained. Then according to the theoretical model *Microsoft Visual Basic* language is used to compile one software, which can be used to calculate and analyze the temperature field and the heat flows' distributions for horizontal buried pipes of the heat exchanger in GSHP.

5. SIMULATED RESULTS AND ANALYSIS

5.1 Impact of Soil Thermal Conductivity

This part reports under winter condition the thermal performance of heat exchanger and soil temperature field around horizontal pipe with the change of soil thermal conductivity from 1.1 W/(m·K) to 2.5 W/(m·K). The pipes of polyethylene (PE) are adopted with thermal conductivity (λ_p) 0.35 W/(m²·°C), density(ρ_p) 1230 kg/m³ and specific heat (C_p) 1.51 kJ/(kg·°C), which are buried in single layer with 1.2m depth and 300mm space between pipes. The diameter and pipe wall thickness are designed as 25×2mm. The fluid in the pipes is water. Soil with sandstone is adopted in simulation with its density (ρ_s) 2400kg/m³ and specific heat (C_s) 0.921 kJ/(kg·°C).

Three points above the pipe in vertical direction are chosen, A (0, 1.1855), B (0, 0.9), C (0, 0.6). With the model and software developed above, soil temperature of the three points with different thermal conductivity are calculated, the results as shown in Fig.2. And another group of points which are symmetrical with the three points mentioned above, A'(0,1.2145), B'(0,1.5), C'(0,1.8), below the pipe, are chosen and simulated in the same way, seen in Fig.3.

Soil temperature field in horizontal direction is distributed symmetrically with $x=0$. Fig. 4 shows the emulation results of six points in horizontal direction, three at the right of pipe, D(0.0145,1.2), E(0.3,1.2), F(0.6,1.2) and three at the left D'(-0.0145,1.2), E'(-0.3,1.2), F'(-0.6,1.2). A, A', D, D' locate at the

same circle which is away from 0.0145m to the centre of a pipe, namely these four points are on the outside surface of pipe, and used to show the temperature change of pipe outside wall with soil thermal conductivity.

The following conclusions can be gotten from Fig. 2 to Fig. 4.

(1) Each curve in the three figures has downward trend, but it is not steep, which denotes that soil temperature around the buried pipe decrease with the increase of soil thermal conductivity.

(2) The range of this kind of decreasing in three curves in every picture is different, which is related to the distance from buried pipe to the site. If the site is more nearer to the buried pipe, soil temperature vary with soil thermal conductivity much faster. This is because that with the increase of soil thermal conductivity, heat transfer quantity between pipe and soil increases, namely pipe can drawing more heat from soil and soil temperature is reduced. And more closer to the pipe, more fast the soil temperature is reduced.

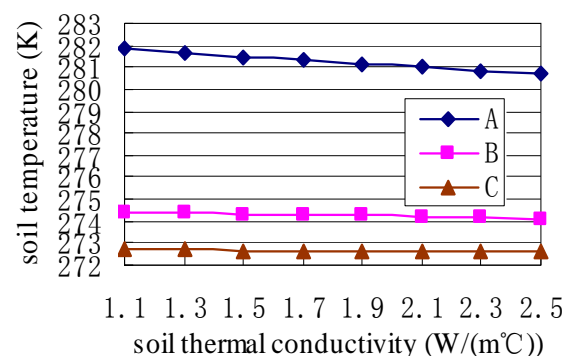


Fig. 2 Soil temperature at vertical three points above pipe vs. soil thermal conductivity

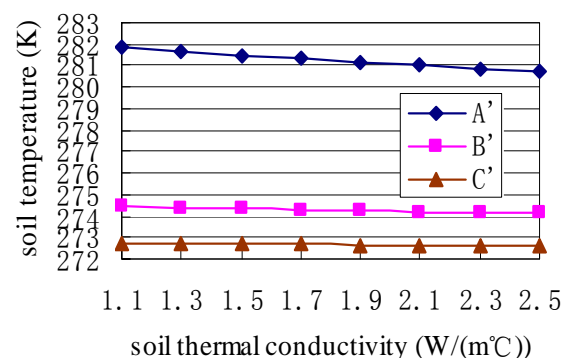


Fig. 3 Soil temperature at vertical three points

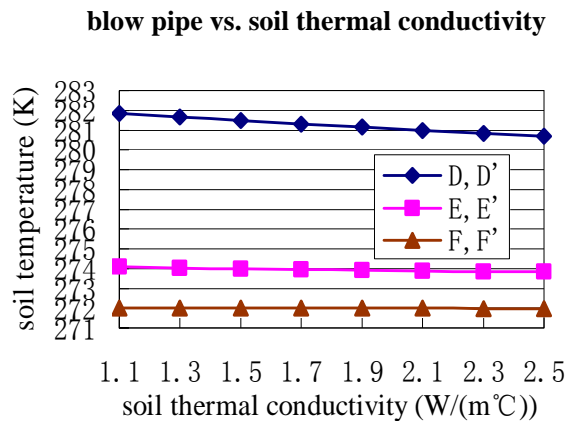


Fig. 4 Soil temperature at horizontal six points vs. soil thermal conductivity

(3) The number value of each curve in Fig. 2 is slightly smaller than that of corresponding curve in Fig. 3. This may be explained by the fact that the influence of atmosphere to soil above the pipe ($y < 1.2$) is bigger than that to soil below the pipe ($y > 1.2$). And atmosphere temperature is lower than soil temperature in winter, so the temperature of soil above the pipe drops fast, and that of soil below the pipe drops relatively slow.

Fig. 5 depicts the change of soil temperature on one circle under different soil thermal conductivity. The center of the circle is the same with that of the buried pipe and its radius is 0.1m. Twelve points for calculating are chosen by dividing circle with the central angle of $\pi/6$. And the soil temperature distribution curve is drawn as shown in Fig. 5. The following conclusions can be get from this figure.

(1) Soil temperature distribution along the circle presents a sine curve. Under winter condition, temperature peak (curve crest) appears in the site of $3\pi/2$, namely the bottom of circle, and rock bottom (curve trough) presents at $\pi/2$, namely the top of circle.

(2) The amplitude of three curves is not changed obviously, which indicates the range of temperature change just slightly decrease with the increase of soil thermal conductivity.

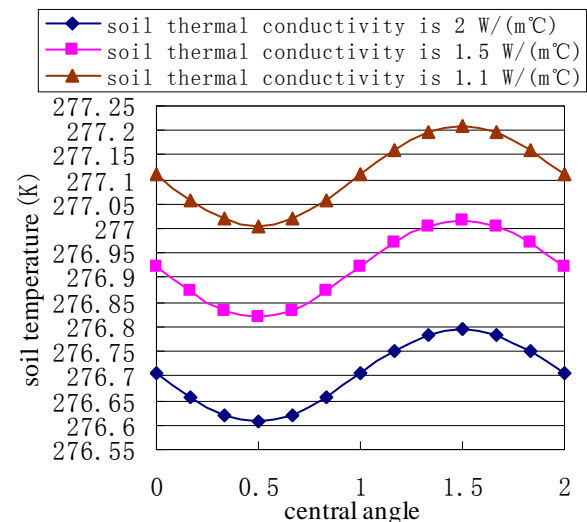


Fig. 5 Change of soil temperature on the circle under different soil thermal conductivity (The center of the circle is the same with that of the buried pipe and its radius is 0.1m)

(3) The bigger soil thermal conductivity is, the lower centre line of the sine curve is, which illustrates that with the increase of soil thermal conductivity, soil temperature is reduced. And when thermal conductivity is 1.1 W/(m·K), soil average temperature on the circle is 277.11K; when thermal conductivity is 1.5 W/(m·K), soil average temperature on the circle is 276.92K; and when thermal conductivity 2 W/(m·K), soil average temperature on the circle is 276.70K.

Fig. 6 shows heat transfer quantity of one-meter length pipe changes with soil thermal conductivity. With the increase of soil thermal conductivity, heat transfer quantity obviously increases. And when thermal conductivity increases from 1.1 W/(m·K) to 2.5 W/(m·K), heat transfer quantity rise from 16.98 W/m to 34.11 W/m, which is estimated to increase about 100.8%. It indicates that soil thermal conductivity have great influence on heat transfer.

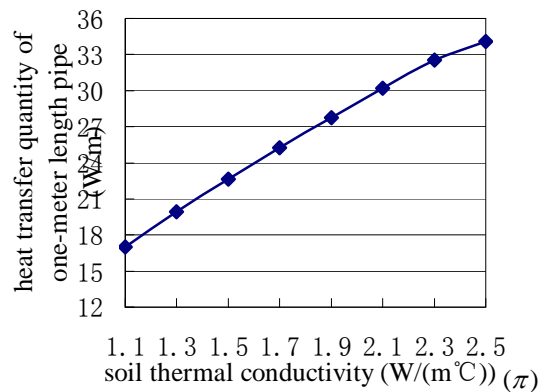


Fig. 6 Heat transfer quantity of one-meter length pipe vs. soil thermal conductivity

5.2 Impact of Pipe Thermal Conductivity

This part reports under winter condition the thermal performance of heat exchanger with different material of pipe, namely with the change of pipe thermal conductivity from 0.19 W/(m·K) to 0.5 W/(m·K). Soil with sandstone is adopted in simulation with its thermal conductivity (λ_p) 2 W/(m²°C), density (ρ_s) 2400kg/m³ and specific heat (C_s) 0.921 kJ/(kg°K). And other conditions are the same with 5.1.

The simulated results that mean temperature of the buried pipe outside surface and heat transfer quantity of one-meter length pipe change with the thermal conductivity of pipe are shown in Fig. 7.

It can be found in Fig.7 that with the increase of pipe thermal conductivity the quantity of heat transfer obviously increases, namely the buried pipe can absorb more heat energy from soil. But the rate of this increasing is reduced with the increase of pipe thermal conductivity.

It is also indicated from Fig.7 that with the increase of pipe thermal conductivity, the mean temperature of the buried pipe outside surface decreases. this is because one of model suppose is that the temperature of fluid in pipe is constant, and the temperature of pipe inside surface is same with that of fluid. And when heat transfer quantity increases, the constant temperature of inside surface results in the increasing

of outside surface. So the conclusions of two curves are congruous.

Heat transfer quantity of several common used pipes are calculated, and compared with that of PVC with thermal conductivity 0.14 W/(m·K). The calculated results are shown in table 3.

It can be seen from table 3, thermal conductivity of polyethylene pipe with high density is greater than that of PVC about 3 times, and heat transfer quantity of polyethylene pipe with high density is higher 23.75% to 26.25% than that of PVC. So, according to the analysis above, it is suggested to adopt polyethylene pipe with high density as buried pipe of underground heat exchanger in heat pump.

6. CONCLUSIONS

In this paper the composition and thermal property of soil are discussed. And the impact of soil thermal conductivity and pipe thermal conductivity on soil temperature field around buried pipe and thermal performance of heat exchanger are simulated. The following conclusions can be gained.

(1) Soil temperature around the buried pipe decreases with the increase of soil thermal conductivity under winter condition. And if the site is more nearer to the buried pipe, soil temperature vary with soil thermal conductivity much faster.

(2) Soil temperature distribution along the circle presents a sine curve. Under winter condition, temperature peak appears at the bottom of circle, and rock bottom appears on the top of circle.

(3) With the increase of soil thermal conductivity, heat transfer quantity obviously increases. And when thermal conductivity increases from 1.1 W/(m·K) to 2.5 W/(m·K), heat transfer quantity is estimated to increase about 100.8%.

(4) With the increase of pipe thermal conductivity, heat transfer quantity and the mean temperature of the buried pipe outside surface all increase. It is suggested to adopt polyethylene pipe with high density as buried pipe in heat pump because its heat transfer quantity is higher 23.75% to 26.25% than that of PVC.

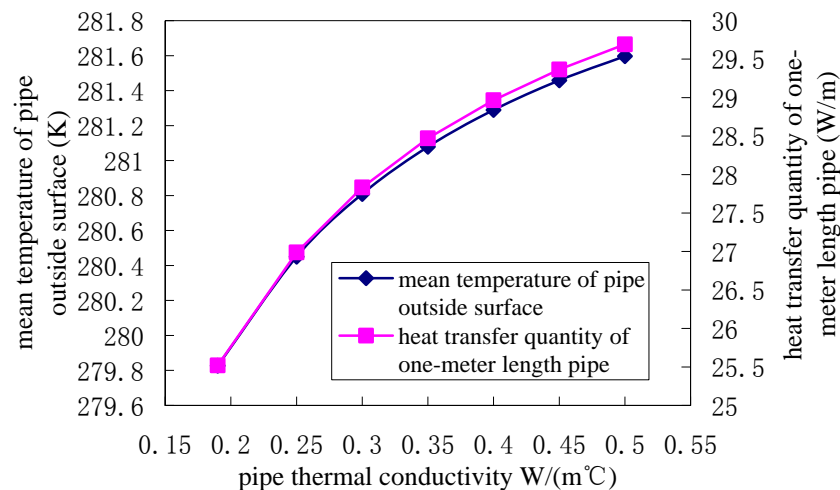


Fig. 7 The mean temperature of the buried pipe outside surface and the heat transfer quantity of one-meter length pipe vs. thermal conductivity of pipe

Tab. 3 Heat transfer quantity of different types of pipes

Type of pipe	Heat transfer quantity of one-meter length pipe $q_l (W/m)$	Comparative increasing degree to PVC with thermal conductivity $0.14 W/(m \cdot ^\circ C)$
PVC	23.6~25.52064	0~8.09%
PE	28.47	20.59%
PE	29.22~29.81	23.75~26.25%
PP-R	26.79	13.45%
PB	26.57	12.53%
PAP	29.37	24.38%

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